Amendments to the Specification

Replace the paragraph spanning pages 3 and 4 with the following:

Figs. 6a and 6b illustrate the output optical spectra of the phase conjugator / wavelength converter of Fig. 4b (using two single-polarisation fibre DFB lasers, where:

the polarsation states of the two pump lights are othogonal (Fig. 6a); and

the polarsation states of the two pump lights are aligned (Fig. 6b); :

Fig. 7 is a schematic diagram of a prior art fibre grating fabrication apparatus;

Figs. 8a to 8c are schematic diagrams showing a prior art grating fabrication process by repeated exposures;

Figs. 9a and 9b are schematic timing diagrams showing the modulation of a UV beam; and

Figs. 10a and 10b are schematic graphs characterising a 20cm grating produced by the apparatus of Figure 7.

Replace the paragraph spanning pages 4 and 5 with the following:

The DFB fibre lasers are written in a Deuterium loaded Er^{3+}:Yb^{3+} -doped fibre, to achieve increased pump absorption, with characteristics described elsewhere [8]. An intra-cavity frequency doubled Ar-ion laser operating CW at 244 nm with 100 mW output is used as the UV source. The grating forming the DFB laser was written using techniques and apparatus described in GB9617688.8, but other known techniques could instead be used.

According to GB9617688.8, an optical waveguide (e.g. an optical fibre) grating having a plurality of grating lines of refractive index variation is fabricated by a method comprising the steps of:

(i)   repeatedly exposing a spatially periodic writing light pattern onto a photosensitive optical waveguide; and

(ii)   moving the writing light pattern and/or the waveguide between successive exposures of the writing light pattern, so that each of at least a majority of the grating lines is generated by at least two exposures to different respective regions of the writing

light pattern. Specific embodiments provide a number of advantages over previous techniques:

1.   The realisation that the laser does not have to be pulsed but just has to be on for a particular duty cycle - preferably less than 50% of the period. This allows an externally modulated CW (continuous wave) laser to be used.

2.   With this technique the grating lines are re-written by several successive exposures of the writing light beam at every grating period (or integral number of grating periods). Thus the footprint defined by the writing light beam is significantly overlapped with the previous lines. Significant averaging of the writing process is achieved thus improving the effective accuracy and resolution of the system, compared to that of R. Stubbe et al, postdeadline paper 1, Proc. Photosensitivity and Quadratic Nonlinearity in Glass Waveguides, Portland, Oregon, September 9-11, 1995, where a group of lines is written in a single exposure, and the fibre is then advanced to a fresh portion where a further group of lines is written in a single exposure.

3.   Effectively controlling the grating writing process on a line-by-line basis allows accurate apodisation to be achieved. This may be performed by dithering the grating writing interferometer position in the fibre to wash out or attenuate the grating strength whilst keeping the average index change constant.

4.   The technique offers the further advantage that the CW laser may be extremely stable, whereas pulsed lasers (e.g. those used in R. Stubbe et al, *supra*) may suffer from pulse-to-pulse instability which is not averaged. In addition the high peak powers of the pulsed laser may cause non-linear grating writing effects.

5.   Arbitrary phase profiles and in particular a linear chirp can be built up by inducing phase shifts electronically along the grating as it grows. In a similar manner to the "Moving fibre/phase mask" technique M.J. Cole et al, Electronics Letters, Vol 31 (17), pp 1488-9, 1995, the maximum wavelength is inversely proportional to the beam diameter. This can be further improved in particular embodiments by incorporating a short, linearly chirped phase mask.

Thus as the fibre is scanned the UV beam may be also slowly scanned across the phase mask, an additional small phase shift is induced, whilst most significantly providing access to writing lines of a different period allowing larger chirps to be built up.

GB9617688.8 also provides apparatus for fabricating an optical fibre grating having a plurality of grating lines of refractive index variation, the apparatus comprising:

a writing light beam source for repeatedly exposing a spatially periodic writing light pattern onto a photosensitive optical waveguide; and

means for moving the writing light pattern and/or the waveguide between successive exposures of the writing light pattern, so that each of at least a majority of the grating lines is generated by at least two exposures to different respective regions of the writing light pattern.

Fig. 7 is a schematic diagram of the fibre grating fabrication apparatus of GB9617688.8. An optical fibre (e.g. a single mode photorefractive fibre) 310 is mounted on a crossed roller bearing translation stage 320 (such as a Newport PMLW160001) which allows for a continuous scan over 40cm. The fibre 310 is positioned behind a short (~ 5mm) phase mask 330 (e.g. a mask available from either QPS or Lasiris). The fibre is continuously and steadily linearly translated or scanned in a substantially longitudinal fibre direction during the grating exposure process. Ultraviolet (UV) light at a wavelength of 244nm from a Coherent FRED laser 40 is directed to the fibre/phase mask via an acoustic-optic modulator 50 (e.g. a Gooch & Housego, M110-4(BR)) operating on the first order.

The relative position of the fibre to the interference pattern of the phase mask is continuously monitored with a Zygo, ZMI1000 differential interferometer 355. The interferometer continuously outputs a 32-bit number (a position value) which gives the relative position with a ~ 1.24nm resolution. This output position value is compared by a controller 370 with switching position data output from a fast computer 360 (e.g. an HP Vectra series 4 5/166 with National Instruments AT-DIO-32F) in order that the controller can determine whether the UV beam should be on or off at that position. Whether the UV beam is in fact on or off at any time is dependent on the state of a modulation control signal generated by the controller 370 and used to control the acousto-optic modulator 350.

So, as each position value is output by the interferometer, the controller 370 compares that position value with the switching position data currently output by the computer 360. If, for illustration, the interferometer is arranged so that the position values numerically increase as the fibre scan proceeds, then the controller 370 detects

when the position value becomes greater than or equal to the current switching position data received from the computer 360. When that condition is satisfied, the controller 370 toggles the state of the modulation control signal, i.e. from "off" to "on" or vice-versa. At the same time, the controller 370 sends a signal back to the computer 60 requesting the next switching position data corresponding to the next switching position.

If the fibre was scanned with the UV beam continuously directed onto the fibre, no grating would be written since the grating lines would be washed out by the movement. However if the UV beam is strobed or modulated (under control of the switching position data generated by the computer 60) with a time period matching or close to:

phase mask projected fringe pitch/fibre translation speed

then a long grating would grow.

This expression is based on a time period of a temporally regular modulation of the UV beam, and so assumes that the fibre is translated at a constant velocity by the translation stage. However, more generally, the switching on and off of the UV beam is in fact related to the longitudinal position of the fibre, so that in order to generate a grating the UV beam should be turned on and off as the fibre is translated to align the interference pattern arising from successive exposures through the phase mask.

Figs. 8a to 8c are schematic diagrams showing a grating fabrication process by repeated exposures of the fibre to the UV beam. In Fig. 8a, the UV beam from the acousto-optic modulator 350 passes through the phase mask 330 to impinge on the fibre 310. During the exposure process, the fibre 310 is being longitudinally translated by the translation stage 320 in a direction from right to left on the drawing. Fig. 8a illustrates (very schematically) a refractive index change induced in the fibre by a first exposure through the phase mask.

Figs. 8a to 8c illustrate a feature of the normal operation of a phase mask of this type, namely that the pitch of the lines or fringes of the interference pattern projected onto the fibre (which gives rise to the lines of the grating) is half that of (i.e. twice as close as that of) the lines physically present (e.g. etched) in the phase mask. In this

example, the phase mask has a "physical" pitch of 1μm, and the lines projected onto the fibre have a pitch of 0.5μm.

The UV beam is modulated by the acousto-optic modulator in a periodic fashion synchronised with the translation of the fibre. In this way, successive exposures, such as the two subsequent exposures shown in Figs. 8b and 8c, generate periodic refractive index changes aligned with and overlapping the first exposure of Fig. 8a. Thus, the refractive index change providing each individual grating "element" or fringe is actually generated or built up by the cumulative effects of multiple exposures through different parts of the phase mask as the fibre moves along behind the phase mask. This means (a) that the optical power needed to generate the grating can be distributed between potentially a large number of exposures, so each exposure can be of a relatively low power (which in turn means that the output power of the laser 340 can be relatively low); and (b) the grating can be apodised by varying the relative positions of successive exposures.

Although each of the successive exposures of the fibre to UV light through the phase mask 330 could be a very short pulse (to "freeze" the motion of the fibre as the exposure is made), this has not proved necessary and in fact there can be used an exposure duty cycle in a range from below 10% to about 50%, although a wider range of duty cycles is possible. An example of a simple regular exposure duty cycle is shown schematically in Fig. 9a, which in fact illustrates the state of the modulation control signal switching between an "on" state (in which light is passed by the acousto-optic modulator) and an "off" state (in which light is substantially blocked by the acousto-optic modulator). The period, τ, of the modulation corresponds to the time taken for the fibre 310 to be translated by one (or an integral number) spatial period of the interference pattern generated by the phase mask 330.

As the duty cycle for the UV exposure increases, the grating contrast decreases (because of motion of the fibre during the exposure) but the writing efficiency increases (because more optical energy is delivered to the fibre per exposure). Thus, selection of the duty cycle to be used is a balance between these two requirements.

Assuming linear growth, the index modulation, $n_g(z)$ in an ideal grating can be described as a raised cosine profile:

$$n_g(z) \propto 1 + \sin(2\pi z/\Lambda)$$

where z is the position down the fibre and Λ the grating period. With this technique one obtains:

$$n_g(z) \propto (\Delta\Lambda_{ON}/\Lambda)[1 + \{\sin(\pi \Delta\Lambda_{ON}/\Lambda)/(\pi \Delta\Lambda_{ON}/\Lambda)\}\sin(2\pi(z+\Delta\Lambda_{ON}/\Lambda)]$$

where $\Delta\Lambda_{ON}/\Lambda$ is the fraction of the period that the beam is on (i.e. the duty cycle). For small values of $\Delta\Lambda_{ON}/\Lambda$ a near 100% grating contrast is obtained however the efficiency of the grating writing is reduced to $\sim \Delta\Lambda_{ON}/\Lambda$ because most of the UV beam is prevented from reaching the fibre. The maximum grating strength is obtained for $\Delta\Lambda_{ON}/\Lambda=0.5$ however the ratio of dc to ac index change is worse. For $\Delta\Lambda_{ON}/\Lambda>0.5$ the grating begins to be reduced whilst the dc index change continues to build. Experimentally, a good value for $\Delta\Lambda_{ON}/\Lambda$ has been found to be ~ 0.3-0.4.

Thus, with embodiments of this technique, exposure of the grating lines or elements is repeated every grating period. Thus the footprint defined by the UV beam, which might for example for a 500µm diameter beam, ϕ_{beam}, consists of $\phi_{beam}/\Lambda(\sim 1000)$ lines, is significantly overlapped with the previously exposed lines. Significant averaging of the writing process given by $(\phi_{beam}/\Lambda)^{\frac{1}{2}}$ is therefore achieved, thus improving the effective accuracy and resolution of the system.

The computer in this embodiment actually generates the switching positions internally as "real" numbers (subject to the limitation of the number of bits used), but then converts them for output to the controller into the same unit system as that output by the Zygo interferometer, namely multiples of a "Zygo unit" of 1.24µm. This internal conversion by the computer makes the comparison of the actual position and the required switching position much easier and therefore quicker for the controller. A random digitisation routine is employed in the computer 360 to avoid digitisation errors during the conversion from real numbers to Zygo units. This involves adding a random amount in the range of ±0.5 Zygo units to the real number position data before that number is quantised into Zygo units. Thus an effective resolution can be obtained of:

$$1.24\text{nm}/(\phi_{beam}/\Lambda)^{\frac{1}{2}} \approx 0.03\text{nm}.$$

The technique offers the further advantage that the CW laser is extremely stable whereas pulsed lasers (as required in the technique proposed by Stubbe et al, *supra*) may suffer from pulse-to-pulse instability which, in the Stubbe et al technique, is not averaged over multiple exposures. In addition the high peak powers of a pulsed laser may cause non-linear grating writing effects, which are avoided or alleviated by using longer and repeated exposures in the present technique.

A refinement of the above technique, for producing apodised gratings, will now be described with reference to Fig. 9b. Using the techniques described above, effectively controlling the grating writing process on a line-by-line basis allows accurate apodisation to be achieved. Apodisation is achieved by effectively dithering the grating writing interferometer position in the fibre to wash out or attenuate the grating strength. However, if the overall duty cycle of the exposure is kept the same, and just the timing of each exposure dithered, the average index change along the grating is kept constant.

To completely wash out the grating subsequent on periods of the UV laser are shifted in phase (position) by $\pm \pi/2 (\pm \Lambda/4)$. To achieve a reduced attenuation the amplitude or amount of dither is reduced. Fig. 9b illustrates an applied dither of about $\pm \pi/3$ from the original (undithered) exposure times. This technique of apodising is better with an exposure duty cycle of less than 50%, to allow a timing margin for 100% apodisation.

One example of the use of this technique is to generate a grating with a contrast increasing at one end of the grating according to a raised cosine envelope, and decreasing at the other end of the grating in accordance with a similar raised cosine envelope, and remaining substantially constant along the central section of the grating. This apodisation can be achieved particularly easily with the present technique, as the central section requires no phase shift between successive exposures, and the two raised cosine envelopes require a phase shift that varies linearly with longitudinal position of the fibre.

The required phase shifts can be calculated straightforwardly by the computer 360, under the control of a simple computer program relating required phase shift to linear position of the fibre (effectively communicated back to the computer 360 by the controller 370, whenever the controller 370 requests a next switching position data value).

Other apodisation schemes are also possible. Compared with previous methods of dithering such as that of M.J. Cole et al, Electronics Letters, Vol 31 (17), pp 1488-9, 1995, this technique is not limited by the dynamics of a mechanical stage used for dithering, but instead simply adjusts the switching time of a nonmechanical modulator element 350. It can also achieve substantially instantaneous phase shifts.

Furthermore, arbitrary phase profiles and in particular a linear chirp can be built up by the computer 360 inducing phase shifts along the grating as it is fabricated. In a similar manner to the "Moving fibre/phase mask" technique of M.J. Cole et al, the maximum wavelength is inversely proportional to the beam diameter. However, with the technique of GB9617688.8, an improvement can be obtained (with respect to the technique of M.J. Cole et al) by incorporating a short, linearly chirped phase mask. Thus as the fibre is scanned the UV beam is also slowly scanned (by another PZT translation stage, not shown) across the phase mask. This scanning of the position of the UV beam in itself induces a small chirp, in accordance with the techniques described in reference M.J. Cole et al, *supra*, but more significantly the translated beam accesses writing lines of a different period allowing larger chirps to be built up. This has been tested using a 19mm diameter, ~ 20nm chirped phase mask (sourced from Lasiris) with its central period around 1070nm. This allows ~ 30nm chirped gratings centred around a central wavelength of 1550nm to be fabricated.

Figures 10a and 10b are schematic graphs showing the characterisation of a 20cm linearly chirped grating written at a fibre translation speed of 200μm/s with the basic technique described earlier, i.e. with a fixed mask. At this fibre translation speed, for a projected fringe pitch of 0.5μm the writing light beam is switched at a switching rate of 400Hz. In other words, the fibre advances by one projected fringe between exposures. (It is noted that the limitation on fibre translation speed in these prototype experiments is the calculation speed of the computer 360 used in experiments, and that given a faster computer such as a Pentium or subsequent generation PC, much higher translation speeds of, say, 10mm per second or more would be possible).

In particular, therefore, Fig. 10a is a graph of reflectivity against wavelength, and Fig. 10b is a graph of time delay against wavelength. The wavelength (horizontal) axes of the two graphs have the same scale, which for clarity of the diagram is recited under Fig. 10b only.

A ~ 4nm bandwidth and dispersion of ~500ps/nm are observed. Gratings up to 40cm and writing speeds up to 1mm/s have been demonstrated. Lengths in excess of 1m and writing speeds up to 10mm/s are feasible.

In the above description, the fibre has been translated with respect to the phase mask, and in the later description the UV beam is translated with respect to the phase mask. However, the important thing is relative motion, and so the choice of which component (if any) remains "fixed" and which is translated is relatively arbitrary.

In regard to the present invention, the ~~The~~ initial horizontal linearly polarisation state of the laser was flipped to a vertical linearly polarised state using a X/2-wave plate. The DFB grating was written with a π-phase shift (identical for both polarisations) off centre [9] by 10% in order to maximise the output to one side of the laser. Up to 50 mW of light from a 980 nm diode was used as pump light. The laser was forward pumped and the polarisation state of the prototype laser was analysed using a HP 8905B polarisation analyser. The phase shift could of course have been different, for example many multiples of π.

Amendments to the Drawings

Please add the attached drawing sheets containing Figs. 7-10.